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February 21, 1979

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TUNNEL 16T PERFORMANCE - TWO- AND THREE-STAGE COMPRESSOR PERFORMANCE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

PWT Tunnel 16T compressor, C1, was operated in a two-stage configuration for the purpose of validating computer predicted results obtained with the COCODEC compressor code. The third rotor row of the three-stage machine was removed and an aluminum shroud was installed to provide a smooth flow passage over the voids created by the blade removal. The compressor was reconfigured to three stages and a verification run was made to ensure that no changes in the compressor performance had occurred during the

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20. ABSTRACT - Continued

two-stage modification and the reinstallation of the third rotor row.

AFSC
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NOMENCLATURE

IGV	Compressor inlet guide vanes
CPRM	Measured compressor pressure ratio
MN	Mach number at the nozzle throat
NCN	Nozzle contour number
N_M	Nozzle contour Mach number
PART NO.	A data subset containing variations of only one independent parameter
PT	Tunnel total pressure, psfa
QM	Measured compressor inlet volume flow, cfs
S1	Compressor first-stage stator blade
S2	Compressor second-stage stator blade
S3	Compressor third-stage stator blade
TT	Tunnel total temperature, °F

1.0 INTRODUCTION

The work reported herein was conducted at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), at the request of the Arnold Engineering Development Center (AEDC/DOTR), under Program Element 65807F. The test was conducted by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number P41T-A6. The test was conducted on January 3 and 9, 1979 in the Propulsion Wind Tunnel (16T) of the Propulsion Wind Tunnel Facility (PWT).

The purpose of the test was to obtain tunnel and compressor performance data with the Tunnel 16T compressor in a two-stage configuration. Data to verify the adequacy of the compressor performance after the three-stage configuration was restored were also obtained. The data from this test will be used to verify the computer predicted compressor performance determined by associated technology efforts.

The final data from this test have been retained at PWT for analysis. Requests for these data should be addressed to the Director of Test Engineering (AEDC/DOTR), Arnold Air Force Station, Tennessee 37389. A copy of the final data is on file on microfilm at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

The AEDC Propulsion Wind Tunnel (16T) is a variable density, continuous-flow tunnel capable of being operated at Mach numbers from 0.2 to 1.6 and stagnation pressures from 120 to 4000 psf. The maximum attainable Mach number can vary slightly depending upon the tunnel pressure ratio requirements with a particular test installation. The maximum stagnation pressure attainable is a function of Mach number and available electrical power. The tunnel stagnation temperature can be varied from about 80 to 160°F depending upon the available cooling water temperature. The test section is 16 ft square by 40 ft long and is enclosed by 60-deg inclined-hole perforated walls of six-percent porosity (see Fig. 1). Additional information about the tunnel, its capabilities and operating characteristics, is presented in Ref. 1.

2.2 TEST INSTALLATION

The test article for this test was the Tunnel 16T compressor. To facilitate the installation of the succeeding test entry, the auxiliary high pitch system (AHIPS) was installed in the test section in addition to the main sting support system. The test section installation is shown in Fig. 1. The orientation of the Tunnel 16T test section and the compressor in the tunnel circuit is shown in Fig. 2.

The Tunnel 16T compressor (C1) is a three-stage, axial-flow machine which is operated at a constant speed of 600 rpm. It is driven by four electric motors developing a combined maximum of 216,000 hp. The design point of the machine is specified as an inlet volume flow of 200,000 cfs at a pressure ratio of 1.385 and at an inlet temperature of 100°F. The general arrangement of the compressor is shown in Fig. 3. Aerodynamic design of the machine is based on the principle of a constant mean swirl. The blading consists of inlet guide vanes, interstage stator blades, rotor blades, and exit guide vanes. The inlet guide vanes, exit guide vanes, and rotor blades are cambered, twisted, and tapered. The interstage stator blades have a constant chord, and the change in camber and radial twist is small. The inlet guide vanes and interstage stator blades are remotely controllable through limits of 29 to -17 deg from the design point to allow selection of specific volume flows through the available range. The exit guide vanes may be adjusted manually. A more detailed description of the compressor may be found in Ref. 2.

The compressor was initially operated in 1956. As a result of a rotor disc structural fatigue failure, the compressor was out of service from August 1961 to April 1965. The rotor assemblies were redesigned to permit construction using rotor blades made of fiberglass instead of stainless steel forgings. The original design of the inlet guide vanes, interstage stator blades, and exit guide vanes was retained in the modified compressor. A comparison between the construction features and the performance of the modified compressor with the original steel bladed compressor may be found in Ref. 3.

The two-stage compressor configuration was achieved by removing the third-stage rotor blades and covering the gap in the compressor hub with aluminum shroud plates. The two-stage configuration is illustrated in Fig. 4.

2.3 TEST INSTRUMENTATION

The compressor performance data were obtained using existing compressor and tunnel monitoring and static pressure instrumentation. Twelve nozzle, twenty test-section ceiling,

installation and removal. Additionally, special procedures, instructions, inspections, and instrumentation were provided for guidance during the two-stage performance investigation. The results of the safety hazard analysis is presented in Appendix A.

3.2 DATA REDUCTION

The standard Tunnel 16T data acquisition and data reduction equations (including the tunnel conditions print option) together with on-line project peculiar data reduction equations were used to reduce the data to engineering units. Standard tunnel parameters compressor interstage static pressures, test section ceiling static pressures and associated parameters were computed, tabulated, and stored on magnetic tape. The IBM 370 computer graphics system was used on-line to assist in the conduct of the test. The compressor rotor blade frequency signatures monitored during the test were reproduced off-line for analysis.

3.3 DATA UNCERTAINTIES

Uncertainties (bands which include 95 percent of the calibration data) of the basic tunnel parameters, shown in Fig. 5, were estimated from repeat calibration of the instrumentation and from the repeatability and uniformity of the test section flow during tunnel calibration. Uncertainties in the instrumentation systems were estimated from repeat calibration of the systems against secondary standards whose uncertainties are traceable to the National Bureau of Standards calibration equipment. The instrument uncertainties are combined using the Taylor series method of error propagation described in Ref. 4 to estimate the uncertainties of the reduced parameters shown below:

Nominal Test Conditions		Uncertainty		
PT(psfa)	TT(°F)	MN	QM(cfs)	CPRM
300	60	±0.025	±3000	±0.009
1000	105	±0.006	±1000	±0.003

4.0 DATA PACKAGE PRESENTATION

A sample of the computed steady-state data is shown in Table 4. The nomenclature for the data tabulation is given in Table 5. In addition to the tabulated data, the data

package consists of magnetic tapes of the steady-state information and blade frequency measurements.

REFERENCES

1. Test Facilities Handbook (Tenth Edition). "Propulsion Wind Tunnel Facility, Vol. 4." Arnold Engineering Development Center, May 1974.

2. Estabrooks, B. B. and Milillo, J. R. "Aerodynamic Performance of the AEDC-PWT Transonic Circuit Compressor." AEDC-TR-57-15 (AD135341), October 1957.

3. Parli, C. L. "Aerodynamic Calibration of the AEDC 16-ft Transonic Tunnel Compressor with Fiberglass Rotor Blades." AEDC-TR-65-242, November 1965.

4. Abernethy, Thompson, et al. "Handbook - Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356), February 1973.

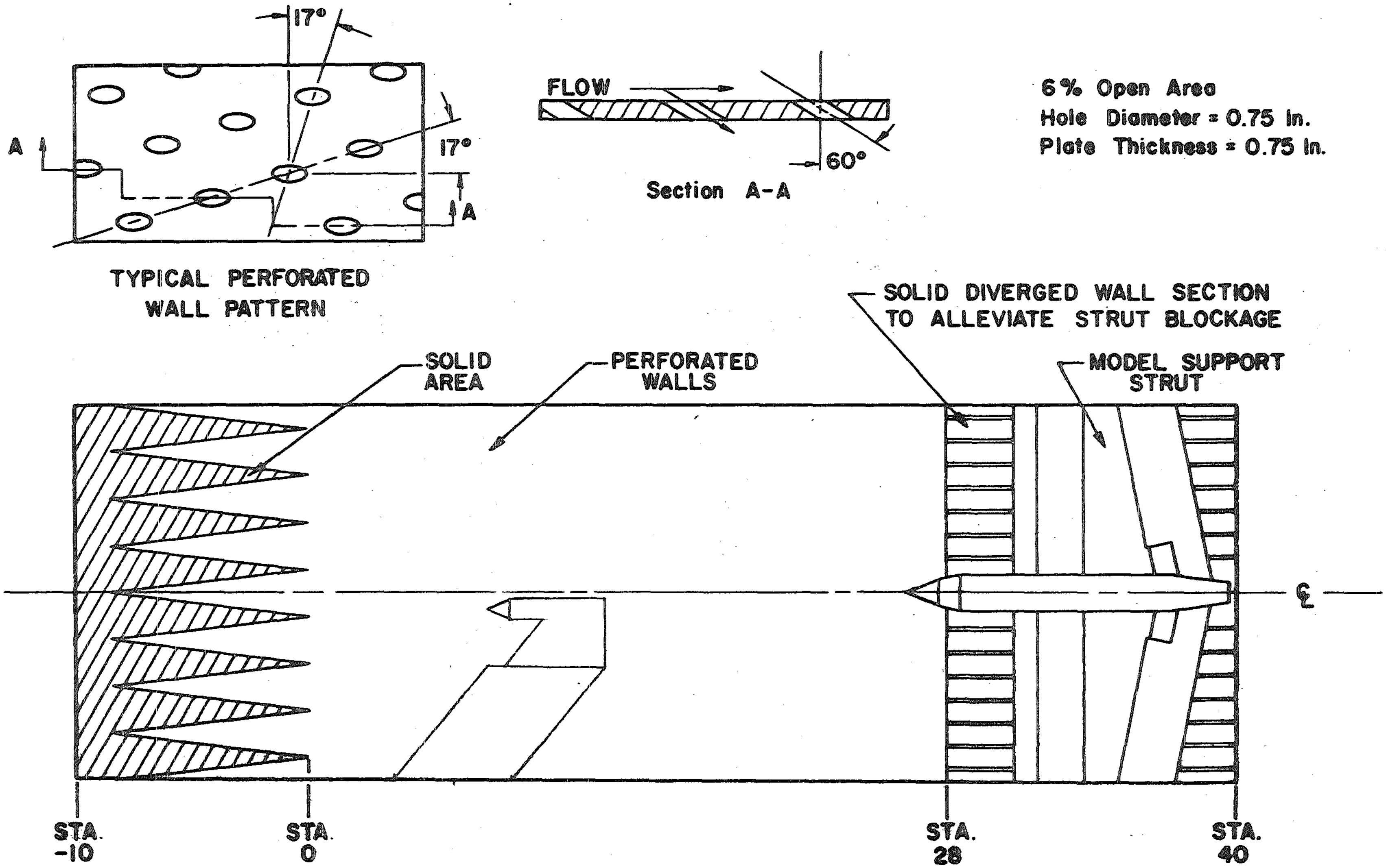


Figure 1. Tunnel 16T Test Section Installation

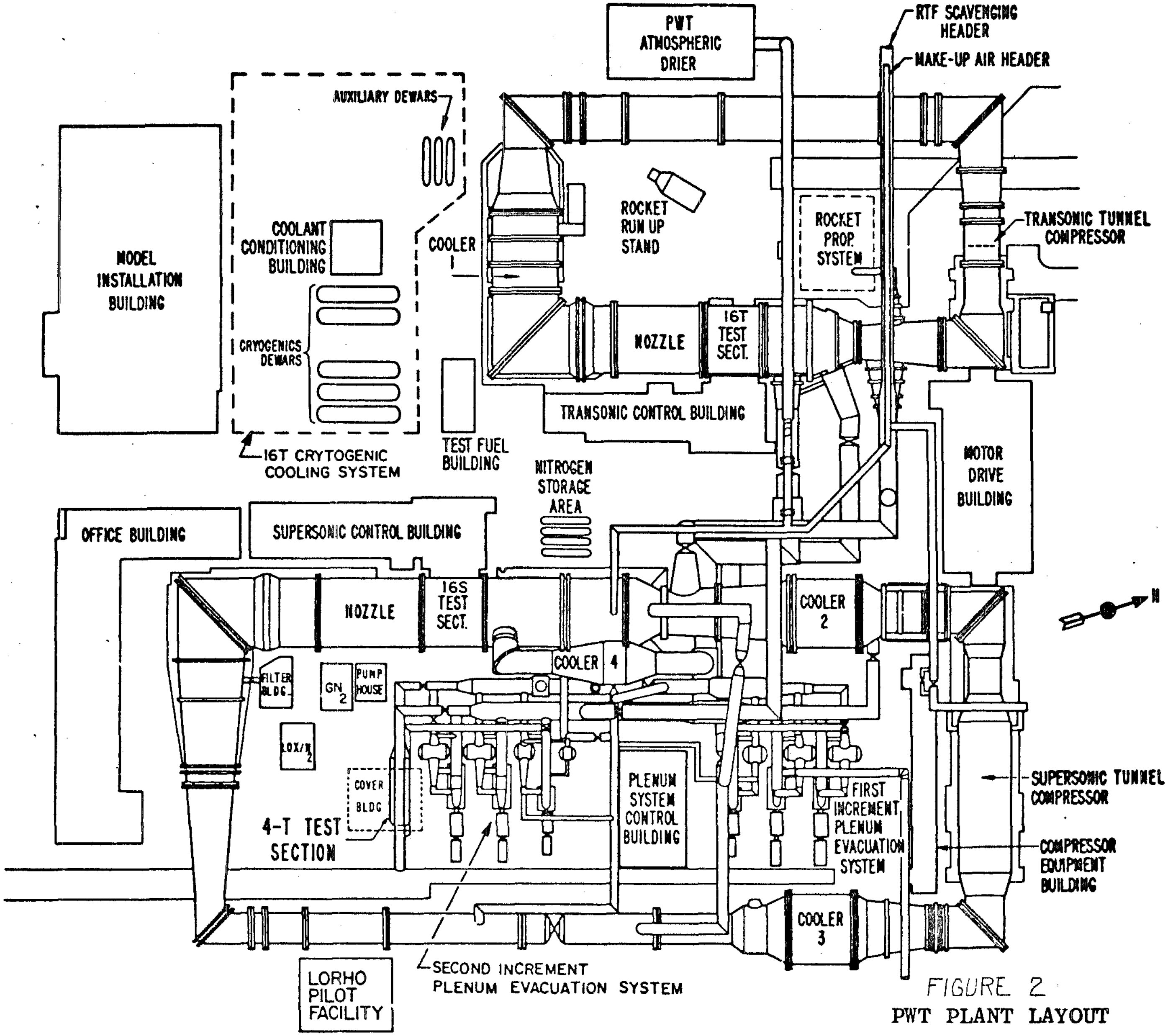


FIGURE 2
PWT PLANT LAYOUT

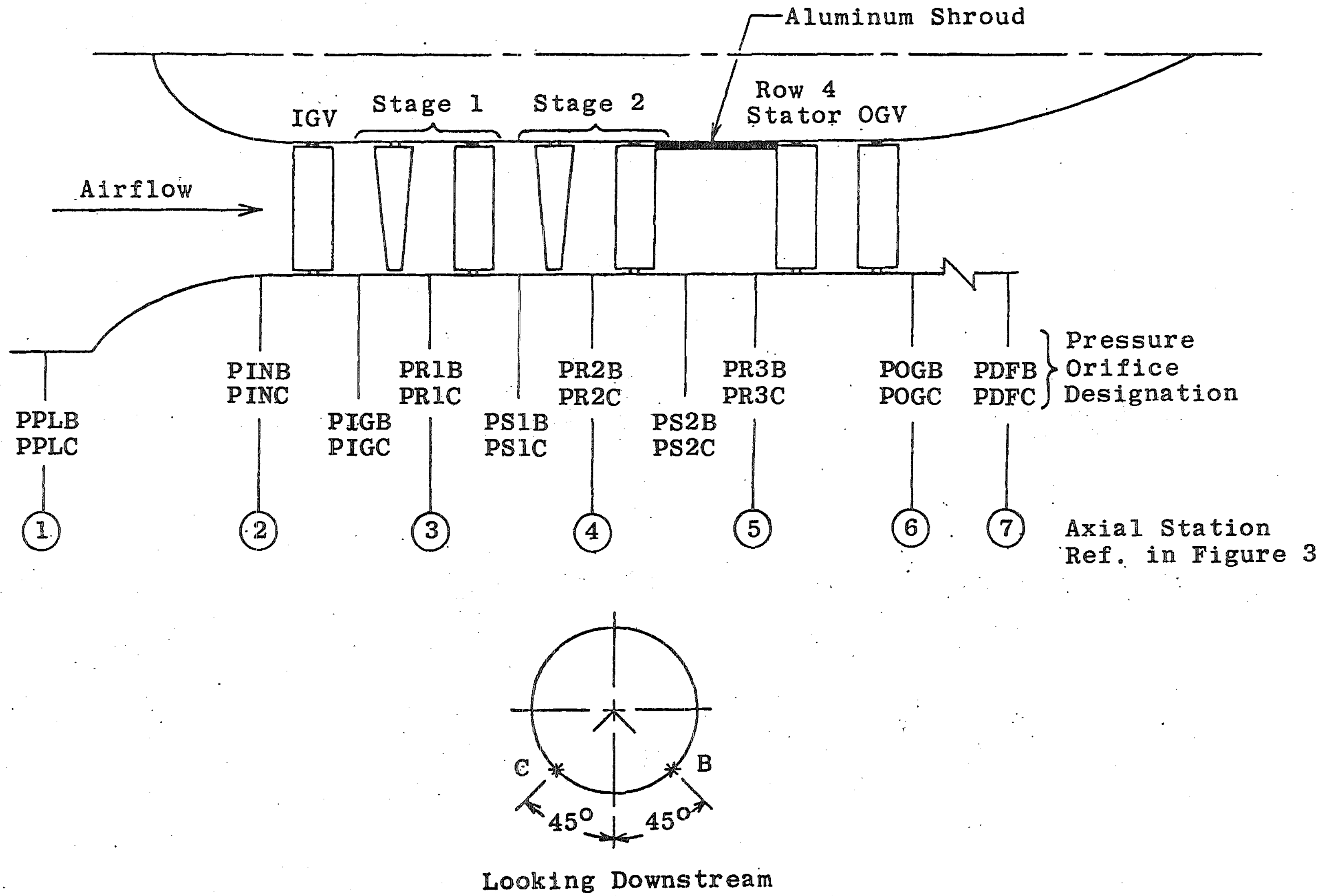


Figure 4. Tunnel 16T Two Stage Compressor Configuration and Instrumentation

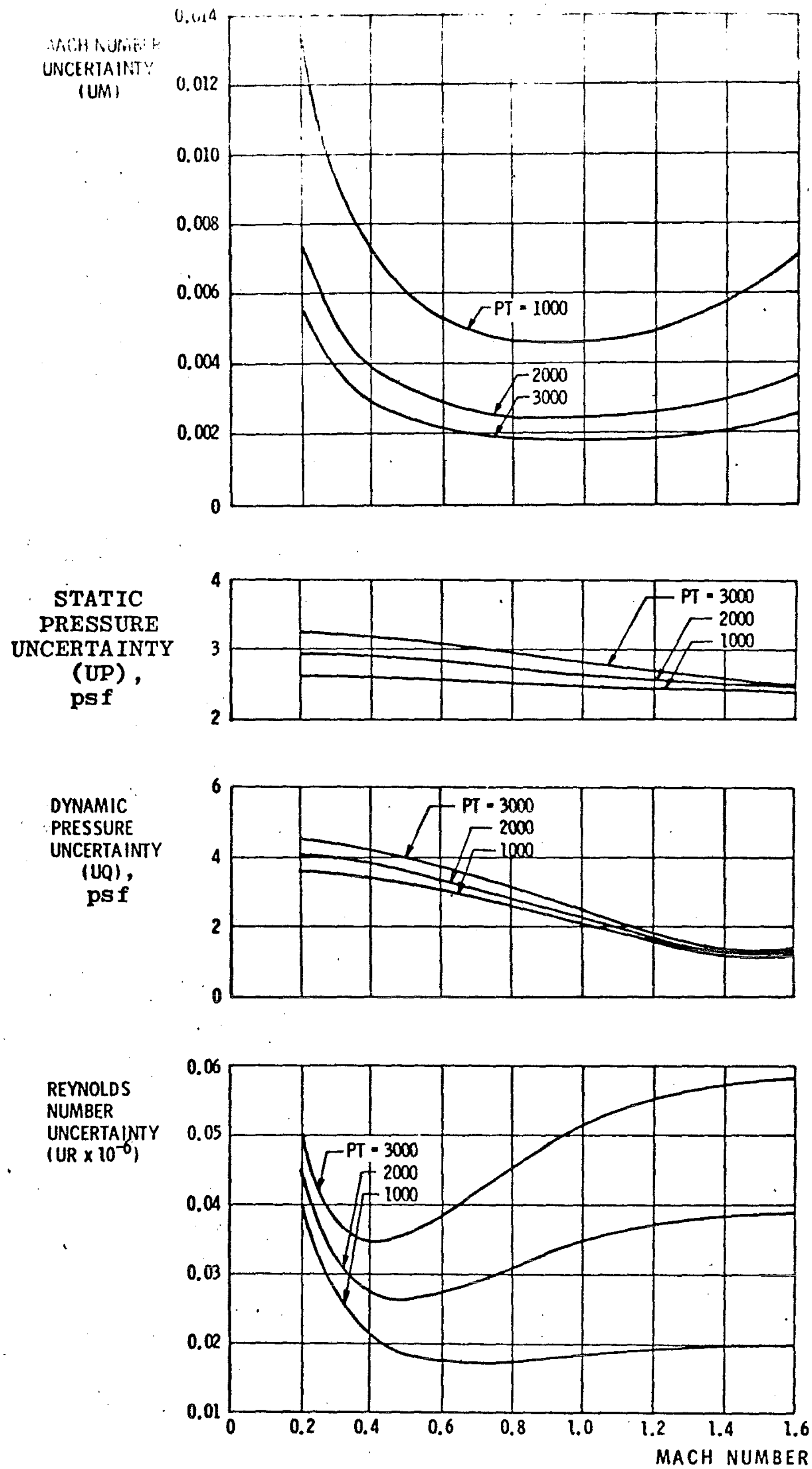


Figure 5. Estimated uncertainties in wind tunnel parameters.

TABLE 1

STATOR BLADE SCHEDULE AT 0 DEG INDEX
TWO STAGE C1 OPERATION
NEGATIVE DIRECTION

STATOR BLADE MISMATCH	ROW 1 CONTROL ROOM COUNTER	ROW 2 CONTROL ROOM COUNTER	ROW 3 CONTROL ROOM COUNTER	ROW 4 CONTROL ROOM COUNTER
(0, 0, 0, 0)	00.00	00.00	00.00	00.00
(0, 0, 0, -3)	00.00	00.00	00.00	-02.51
(0, 0, 0, -6)	00.00	00.00	00.00	-05.03
(0, 0, 0, -9)	00.00	00.00	00.00	-07.48
(0, 0, +9, -6)	00.00	00.00	+07.65	-05.03
(0, 0, +6, -6)	00.00	00.00	+05.12	-05.03
(0, 0, +3, -6)	00.00	00.00	+02.55	-05.03

TABLE 2

STATOR BLADE SCHEDULE WITH (0, 0, +6, -6) MISMATCH
TWO STAGE C1 OPERATION
NEGATIVE DIRECTION

INDEX	ROW 1 CONTROL ROOM COUNTER	ROW 2 CONTROL ROOM COUNTER	ROW 3 CONTROL ROOM COUNTER	ROW 4 CONTROL ROOM COUNTER
+18	+15.05	+15.26	+19.83	+10.22
+17	+14.27	+14.45	+19.06	+09.39
+16	+13.44	+13.60	+18.29	+08.52
+15	+12.64	+12.74	+17.55	+07.65
+14	+11.80	+11.89	+16.72	+06.82
+13	+10.97	+11.05	+15.93	+05.95
+12	+10.13	+10.20	+15.13	+05.13
+11	+09.32	+09.34	+14.31	+04.26
+10	+08.48	+08.49	+13.51	+03.41
+9	+07.64	+07.63	+12.69	+02.56
+8	+06.79	+06.80	+11.86	+01.70
+7	+05.95	+05.95	+11.01	+00.87
+6	+05.12	+05.09	+10.17	+00.00
+5	+04.26	+04.22	+09.36	-00.82
+4	+03.33	+03.37	+08.50	-01.68
+3	+02.52	+02.51	+07.65	-02.51
+2	+01.67	+01.63	+06.81	-03.35
+1	+00.85	+00.81	+05.96	-04.18
0	00.00	00.00	+05.12	-05.03
-1	-00.86	-00.85	+04.28	-05.84
-2	-01.70	-01.70	+03.41	-06.65
-3	-02.57	-02.55	+02.55	-07.48
-4	-03.41	-03.40	+01.69	-08.29
-5	-04.24	-04.22	+00.97	-09.09
-6	-05.09	-05.04	00.00	-09.87
-7	-05.93	-05.91	-00.85	-10.70
-8	-06.78	-06.73	-01.69	-11.46
-9	-07.61	-07.56	-02.54	-12.15
-10	-08.47	-08.35	-03.38	-13.00
-11	-09.27	-09.15	-04.24	-13.76
-12	-10.13	-09.95	-05.08	-14.49
-13	-10.95	-10.74	-05.92	-15.24
-14	-11.77	-11.53	-06.75	-15.26 (LIMIT)
-15	-12.60	-12.31	-07.61	
-16	-13.39	-13.08	-08.46	
-17	-14.22	-13.85	-09.26	

Table 3

Test Matrix Summary

Part No.	Compressor Config.	NCN	N_M	PT(psf)	TT(°F)	Stator Blade Index, deg			
						IGV	S1	S2	S3
5						+ 6	+ 6	+12	0
6	2-stage	1	1.00	300	60	0	0	0	0
						0	0	0	-3
						0	0	0	-6
						0	0	0	-9
						0	0	+ 9	-6
						0	0	+ 6	-6
						0	0	+ 3	-6
23	3-stage					+12	+12	+ 9	+9
24						0	0	0	0
						- 6	- 6	- 6	-6
25		33	1.417			0	0	0	0
						- 6	- 6	- 6	-6
						- 9	- 9	- 9	-9
						-10	-10	-10	-10
						-10.5	-10.5	-10.5	-10.5
26				1000	105	0	0	0	0
						- 6	- 6	- 6	-6
						- 9	- 9	- 9	-9
						-12	-12	-12	-12
						-12.5	-12.5	-12.5	-12.5
27		45	1.604			0	0	0	0
						- 3	- 3	- 3	-3
						- 6	- 6	- 6	-6
						- 6.5	- 6.5	- 6.5	-6.5

DATE 16-JAN-79 PROJECT NO P41T-A6
ARO, INC.
AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
PROPULSION WIND TUNNEL
ARNOLD AIR FORCE STATION, TENNESSEE

Table 4. Sample of Tabulated Data

PART	POINT	PROJECT	TEST	DATE	DAY HR MIN SEC	MODE	DELP	PROC DATE	WIND-OFF	SET	PROPULSION WIND TUNNEL
28	1	P41T-A6	TF-520	1/10/79	10: 0:10: 9	0	400	16-JAN-79	22/ 1	1	TRANSONIC 16T

M	PT	P	Q	REX10-6	TT	TTR	H	PC	DP	WA	TPR	SHX10+3	PTI	PTE	CPR
.005	2067.0	2067.0	0.0	0.031	96.8	556.5	649.	2066.8	0.8	0.00	1.000	0.939	2067.1	2067.3	1.000

PTA	PTB	PCA	PCB	DPA	DPB	MDSYNC	PCD	DP10	TTA	TTB	T10	TDP	WAE	WAW	WASCH	NCN
2067.0	2067.1	2066.8	2066.3	0.2	0.8	0.0	2066.8	0.0	96.8	97.7	69.2	3.0	0.00	0.00	1.0	45.

MC	DM	M1	REMC	WT	WP	WP/WT	PM1	PM2	PM3	PM4	PDI	MWD/PSF	PD0	ECT	CPRC	QCTX10-3
.0118	-0.0058	0.0059	-0.0009	102.2	-0.0	0.0000	0.2	-1.6	1.4	-0.1	-0.2	-0.0001	-0.0	-1.1	1.000	1.462

SBAR1	SBAR2	SBAR3	SBAR4	DWPE	DWPW	WCT	CART	MD	MTOL
17.73	17.70	15.03	11.92	158.0	158.0	101.8	2.0	1.290	0.099

DP71A	PN12A	PN28A	PN32A	PN36A	PN39A	PN40A	MNA	CPRMA	QMAX10-3	WNA	CPRCA	QCAX10-3	PTI3	ECCA
-0.2	2070.3	2070.5	2069.6	2069.6	2066.8	2066.8	0.012	1.000	2.729	190.0	1.000	2.729	2066.6	2.1
DP71B	PN12B	PN28B	PN32B	PN36B	PN39B	PN40B	MNB	CPRMB	QMBX10-3	WNB	CPRCB	QCBX10-3	TRF	ECCB
0.0	2070.3	2069.8	2069.6	2069.0	2066.6	2067.2	0.010	1.000	2.216	154.1	1.000	2.216	120.0	0.0

PPLB	PINB	PIGB	PR1B	PS1B	PR2B	PS2B	PR3B	POGB	PDFB
2067.0	2063.8	2131.1	2068.1	2068.1	2069.6	2067.0	2066.8	2064.9	2066.8
PPLC	PINC	PIGC	PR1C	PS1C	PR2C	PS2C	PR3C	POGC	PDFC
2067.0	2066.6	2070.0	2067.9	2068.1	2069.2	2067.7	2068.1	2066.8	2066.6

CPR1B	CPR2B	CPR3B	BPR1B	BPR2B	BPR3B	BPR4B	BPR5B	BPR6B	BPR7B
0.970	0.999	0.999	1.033	0.970	1.000	1.001	0.999	1.000	0.999
CPR1C	CPR2C	CPR3C	BPR1C	BPR2C	BPR3C	BPR4C	BPR5C	BPR6C	BPR7C
0.999	1.000	1.000	1.002	0.999	1.000	1.001	0.999	1.000	0.999

PES1C	PES2C	PESM1	PESM2	PESMW	MWP/PSF	MWTOT	MW/PSF	V12	V3	V10	V15	EM1	EM2	EM3	EM4	ECMA	ECMB
32.	0.	5.5	0.0	5.5	0.0026	5.3	0.0026	100.9	96.1	0.0	0.0	94.1	67.6	73.5	94.1	2.2	0.0

TEST SECTION CONDITIONS

STA	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
P X	2066.4	2066.7	2066.7	2066.7	2066.6	2066.9	2066.9	2066.7	2066.6	2066.8	2066.7	2066.9	2066.8	2066.6	2066.7	2066.7
M X	0.0197	0.0154	0.0137	0.0137	0.0170	0.0094	0.0062	0.0137	0.0170	0.0118	0.0137	0.0094	0.0118	0.0170	0.0154	0.0137

STA	17.0	18.0	19.0	20.0	MA	2SIG	DELM
P X	2066.8	2066.7	2066.7	2066.4	0.0128	0.0063	-0.0078
M X	0.0118	0.0154	0.0137	0.0209			

Table 5

Tabulated Data Nomenclature

<u>Line 1</u>

PART	Data part number (a data sub-set containing variations of only one independent parameter)
POINT	Test point (a single record of all test parameters)
PROJECT	Test project identification number
TEST	Test number
DATE	Date of data acquisition, month/day/year
DAY	Calendar day number
HR MIN SEC	Time of data acquisition, hr:min:sec
MODE	Code signifying one of several standard or test peculiar data acquisition routines
DELP	Code signifying selection of various primary tunnel condition measurements for data reduction
PROC DATE	Date of computation of data, month-day-year
WIND-OFF	Part and point used for windoff reference, part/point
SET	Constant set number, indicates the constant set used for the data reduction

<u>Line 2</u>

M	Free-stream Mach number
PT	Total pressure, psfa
P	Free-stream static pressure, psfa
Q	Free-stream dynamic pressure, psfa
REX10-6	Reynolds number
TT	Total temperature, °F
TTR	Total temperature, °R

Table 5. Continued

Line 2 - Continued

H	Pressure altitude, ft
PC	Tunnel 16T plenum pressure, psfa
DP	Tunnel differential pressure, PT-PC, psf
WA	Average test section wall angle, deg
TPR	Tunnel pressure ratio
SHx10+3	Tunnel specific humidity
PTI,E	Tunnel compressor inlet/exit pressure, psfa
CPR	Tunnel compressor pressure ratio, PTE/PTI

Line 3

PTA,B*	Total pressure, psfa
PCA,B	Plenum pressure, psfa
DPA,B	Differential pressure, PT-PC, psf
MDSYNC	Main drive on-synch indication
PCD	Plenum pressure, PT-DP, psf
DP10	Pressure differential total minus venturi static at Valve 10, psf
TTA,B	Stagnation temperature, °F
T10	Temperature at Valve 10, °F
TDP	Dew point temperature, °F
WAE	East cart wall angle, deg
WAW	West cart wall angle, deg
WASCH	Desired wall angle schedule
NCN	Nozzle contour number

*A,B indicates redundant measurements of same quantity.

Table 5. Continued

<u>Line 4</u>	
MC	Plenum Mach number
DM	Tunnel calibration factor, $M_\infty - M_C$
M1	Uncorrected test Mach number
REMC	Reynolds number correction to Mach number
WT	Test section weight flow, lb/sec
WP	Plenum weight flow, lb/sec
WP/WT	Weight flow ratio
PM1	M-1 motor power, MW
PM2	M-2 motor power, MW
PM3	M-3 motor power, MW
PM4	M-4 motor power, MW
PDI	Total main drive input power, MW
MWD/PSF	Main drive power factor, MW/psf
PDO	Main drive output power, MW
ECT	Corrected compressor efficiency, percent
CPRC	Corrected compressor pressure ratio using CPR
$QCTX10^{-3}$	Compressor corrected volume flow, cfs
<u>Line 5</u>	
SBAR1,2,3,4	S1,2,3,4 stator blade angle, deg
DWPE	East diffuser wall position, counts
DWPW	West diffuser wall position, counts
WCT	Compressor weight flow, lb/sec
CART	Test cart number
MD	Desired Mach number (constant box)

Table 5. Continued

Line 5 - Continued

MTOL	Desired Mach number tolerance

Lines 6 and 7

DP71A,B	Differential pressure across the compressor, PTE-PTI, psf
PNXY	(x=12,28,32,36,39,40; y=A,B) Nozzle static pressure, psfa
MNA,B	Nozzle Mach number
CPRMA,B	Measured compressor pressure ratio, $\left(\frac{PTI+DP71}{PTI}\right)$
$QMA,BX10^{-3}$	Compressor volume flow based on nozzle Mach number, cfs
WNA,B	Tunnel weight flow based on nozzle Mach number, lb/sec
CPRCA,B	Corrected compressor pressure ratio using CPRMA,B
$QCA,BX10^{-3}$	Corrected compressor volume flow using QMA,B, cfs
PTI3	Tunnel compressor inlet pressure, psfa
TRF	Reference total temperature, °F
ECCA,B	Corrected compressor efficiency using CPRCA,B and QCA,B, percent

Lines 8 and 9

P XY	(x = PL,IN,R1,S1,R2,S2,R3,OG,DF see Fig. 4; y = B,C) Compressor interstage static pressure, psf

Lines 10 and 11

CPRZX	Compressor stage pressure ratio, PYX/PWX (X = B&C; Z = 1,2,3; Y = S1,S2,OG; W = IG,S1,S2), see Fig. 4
BPRZX	Compressor blade pressure ratio, PYX/PWX (X = B&C; Z = 1,2,3,4,5,6,7; Y = IG,R1, S1,R2,S2,R3,OG; W = IN,IG,R1,S1,R2,S2,R3) see Fig. 4

Table 5. Continued

<u>Line 12</u>	
PES1C	Plenum evacuation system (PES) first increment configuration
PES2C	Plenum evacuation system second increment configuration
PESM1	PES first increment motor power, MW
PESM2	PES second increment motor power, MW
PESMW	PES total motor power, MW
MWP/PSF	PES power factor, MW/psf
MWTOT	Tunnel 16T total power, MW
MW/PSF	Tunnel 16T total power factor, MW/psf
V12	Valve 12 position, percent
V3	Valve 3 position, percent
V10	Valve 10 position, percent
V15	Valve 15 position, percent
EMX	(X=1,2,3,4) Main drive motor efficiency, percent
ECMX	(X=A,B) Measured compressor efficiency, percent
<u>Line 13</u>	
STA	Nominal tunnel station, ft
PX	Test section ceiling static pressure, psf
MX	Test section Mach number based on PX
<u>Line 14</u>	
STA	Nominal tunnel station, ft
PX	Test section ceiling static pressure, psf
MX	Test section Mach number based on PX

Table 5. Concluded

<u>Line 14</u> - Continued

MA	Average test section Mach number computed from PX between stations 6 and 18
2SIG	Two standard deviations of test section Mach number tunnel station, MA
DELM	Difference between the calibrated Mach number and the average test section Mach number (M-MA)

ARO SYSTEM SAFETY HAZARD ANALYSIS APPENDIX A

Prepare original and two copies. Forward one copy each to Safety Office and Facility AF Test Director. Keep one copy.

DATE	
December 4, 1978	

ON	FAC/DEPT	BRANCH	SECTION
Tunnel 16T, C1 Compressor	FSD, PWT	P-Plant, 16T Projects	FPO, PB5

OVERALL OPERATION OR PROCESS

C1 Compressor Two Stage Operation (3rd Stage Blades Removed)

ANALYSIS PERFORMED BY:

J. N. Patterson

REMARKS

This analysis is performed in support of Project P41T-A6, 16T Compressor Performance (Phase B) Additional information and sketches are shown in Attachment 1.

This analysis addresses the equipment hazards associated with C1 two stage operation only. Hazards associated with normal operation and personnel safety are covered by existing procedure

ACTIVITY/CONDITION	HAZARD	PREVENTIVE MEASURE
1. Removal of Row No. 3 blades and spacers	1a. Blade or spacer damage from handling and storage.	1a. Established handling and storage methods will be utilized. Applicable portions of maintenance Procedure 262M will be followed.
	1b. Hardware left in tunnel.	1b. An accounting of items removed will be made. Foreign Object Control Procedure No. 000-32 will be utilized
	1c. Tools or equipment left in tunnel.	1c. Existing Foreign Object Contol Procedure 000-32 will be utilized. Each tool taken into tunnel will be accounted for and established procedures followed.
2. Installation of Aluminum Shroud Fairing	2a. Incorrect installation	2a. Special instructions will be prepared to ensure proper installation of all components in accordance with Dwg. PT006545. An inspection will be performed by engineering personnel.
	2b. Fairing structural failure	2b. A detailed stress analysis has been performed. The pressure acorss the plate will be monitored utilizing transducers with adequate response and limited to 1.5 psid. A warning will sound at 1.2 psid.
	2c. Fairing bolt failure	2c. Detailed stress analysis has been performed. New locking nuts will be used and specified torque values will be adhered to.

FURTHER SYSTEM SAFETY TREATMENT IS REQUIRED:

☒ NO ☐ YES. WILL BE DOCUMENTED BEFORE ______ (EST. DATE) (MUST BE EARLIER THAN START OF WORK COVERED.)

Activity/Condition	Hazard	Preventive Measure
	2d. Damage to fairing caused by relative movement of existing stator shrouds	2d. Plate attachment holes are oversized allowing relative movement between No. 3 and No. 4 stator shrouds. Proper bolt torque values are important and will be ensured. (See 2a.)
	2e. Hardware, tools, or equipment left in tunnel	2e. Existing Foreign Object Control Procedure 000-32 will be followed. Tools will be accounted for as in 1c. Additionally a thorough accounting of each new item taken into tunnel will be made.
	2f. Loose bolts and/or nuts	2f. Torque values will be double checked by a second individual. Careful visual inspections will be made by supervisory and engineering personnel after the stall checks are completed.
Compressor operation at high pressure ratio	3a. Inadvertent stall at high power.	3a. Stall line will be defined at P_t = 300 psf. Intentional stalls will not be permitted at higher pressures. All operation will be carefully monitored by the Duty Engineer to prevent stall conditions.
	3b. Damage as a result of 300 psf stall check	3b. A careful and detailed inspection will be made by engineering personnel after stall checks. Special and existing checklist will be used.
	3c. Undetected rotating stall	3c. A microprocessor based system will continuously monitor (2) Row 1 and (2) Row 2 blades for frequencies near the blade natural frequency. This system was developed for C2 and has proven effective in rapid detection and indication of stalled zones.

Activity/Condition	Hazard	Preventive Measure
. Compressor operation at high power	4a. Blade damage from overstressing	4a. Stress analysis has been performed and limits established at 4600 psi bending and ±1100 psi dynamic. Three Row No. 2 and Two Row No. 1 blades will be continuously monitored. Minimum instrumentation requirements specified in FSD/P Checklist P10C-06-01A will be adhered to. Possibility of overstressing other blades will be minimized by setting input power limit at 106 MW. (180 normal with 3rd row blades installed).
5. Removal of fairing shroud and hardware	5a. Failure to remove all material	5a. Special instructions will be provided for removing components. All items removed must correspond to accounting of newly installed items in 2e.
Reinstallation of Row No. 3 blades and components	6a. Incorrect Installation	6a. Reinstallation will conform to existing assembly drawing and instructions. Installation will be inspected by engineering personnel.
	6b. Loose bolts and/or nuts	6b. Each bolt and/or nut will be double checked by a second individual for proper torque.
	6c. Tools, hardware, or equipment left in tunnel.	6c. Foreign Object Control Procedure 000-32 utilized. Tools will be accounted for as in 1c.
	6d. Degradation in performance caused by changes in seal clearance.	6d. Adequacy of compressor performance will be verified by conduct of a stall check in the three stage configuration.

ATTACHMENT No. 1

PROJECT DESCRIPTION

The 3rd stage rotor blades of the Transonic Compressor C1 will be removed and a metal shroud will be installed to cover the opening created. The objectives of the test are: To establish a two-stage Compressor C1 operating map; to determine the potential power savings and tunnel 16T operating limits; and establishment of an experimental data base for comparison to analytical calculations.

COMPRESSOR CONSIDERATIONS

Two stage operation and the modifications required increases the potential for excessive blade stresses (over powering) and foreign object damage. The composite rotor blades have exceeded the designed life cycle and excessive stresses will decrease remaining life and/or result in blade structural failures. The blades are also susceptible to shell damage from loose debris.

The purpose of this analysis is to identify hazards associated with two stage operation and specify preventive measures required to minimize their occurrence.

MODIFICATIONS REQUIRED

Modifications required to insure satisfactory two-stage operation are:

a. Removal of the 33 third row rotor blades and blade spacers.

b. Design and installation of a fairing shroud to provide a smooth cover between the 3rd and 4th row stator blades.

c. Instrumentation for the 2nd row rotor blade stresses must be installed. (Only 1st and 3rd row existing.)

d. Installation of appropriate instrumentation for detecting pressure differential across the fairing shroud.

The above modifications are shown on Dwg. PT006545 and the sketch below.

OPERATING AND STRESS LIMITS

As a result of engineering and design analysis the following operating and component stress limits have been established.

a. Compressor mapping requiring stall conditions will be performed at P_T = 300 psf only. Other data will be obtained at higher pressures with test section flow established.

b. Blade stress limits are:

Centrifigual plus bending = 4600 psi
Dynamic ± 1100 psi
(Strain gage located at 150 in. radius)

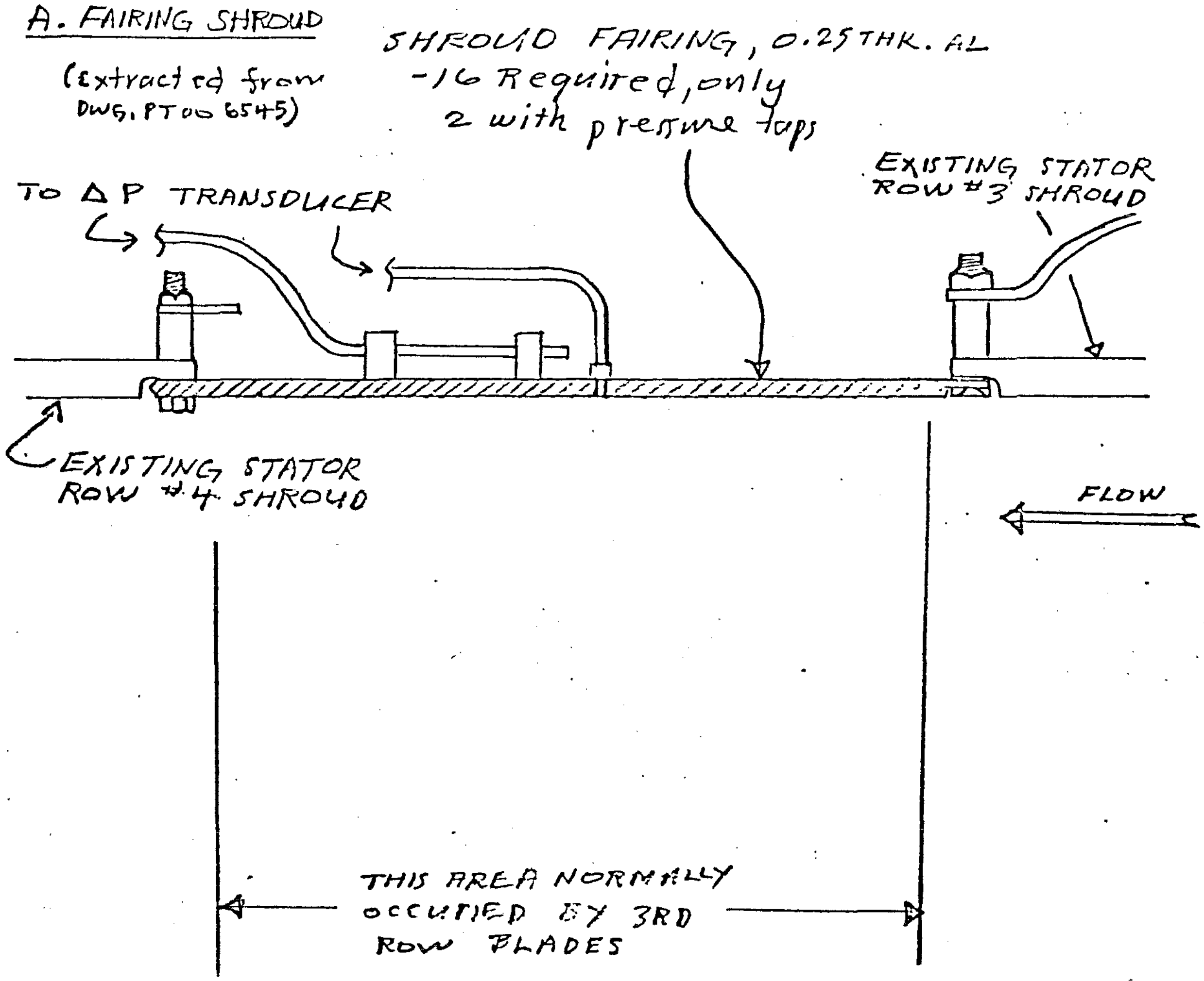
c. The power input to the compressor will be limited to 106 MW to further ensure against non-instrumented blade overstresses.

d. The differential pressure across the shroud will be limited to 1.5 psi. A warning will be provided at 1.2 psi.

SKETCHES

A. FAIRING SHROUD

(extracted from DWG. PT00 6545)



B. BLADE INSTRUMENTATION